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Point-to-point registration with mandibulo-maxillary splint in open and closed jaw position. Evaluation of registration accuracy for computer-aided surgery of the mandible

Bettschart, C ; Kruse, A ; Matthews, F ; Zemann, W ; Obwegeser, J A ; Grätz, K W ; Lübbers, H T

Abstract: INTRODUCTION: Computer navigation plays an increasingly important role in craniomaxillofacial surgery. The difficulties in computer navigation at the craniomaxillofacial site lie in the accurate transmission of the dataset to the operating room. This study investigates the accuracy of the dental-splint registration method for the skull, midface, and mandible. MATERIAL AND METHODS: A synthetic human skull model was prepared with landmarks and scanned with cone beam computer tomography (CBCT). Two registration splints fixed the mandible against the viscerocranium in two different positions (closed vs. open). The target registration error was computed in all 278 landmarks spread over the entire skull and mandible in 10 repeated measurements using the VectorVision(2) (BrainLAB Inc., Feldkirchen, Germany) navigation system. RESULTS: If registered in the closed position an average precision of 2.07mm with a standard deviation (SD) of 0.78mm was computed for all landmarks distributed over the whole skull. Registration in the open position resulted in an average precision of 1.53mm (SD=0.55mm). For single landmarks the precision decreases linearly with distance from the reference markers. The longer the three-dimensional distance between the registration points, the more precise the computer navigation is, mainly in the most posterior area of the cranium. CONCLUSION: Our findings in the cranium are comparable with those of other studies. Artificial fixation of the lower jaw via splint seems to introduce no additional error. The registration points should be as far apart from each other as possible during navigation with the splint.

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ABSTRACT

Introduction

Computer navigation plays an increasingly important role in craniomaxillofacial surgery. The difficulties in computer navigation at the craniomaxillofacial site lie in the accurate transmission of the dataset to the operating room. This study investigates the accuracy of the dental-splint registration method for the skull, midface, and mandible.

Material and Methods

A synthetic human skull model was prepared with landmarks and scanned with cone beam computer tomography (CBCT). Two registration splints fixed the mandible against the viscerocranium in two different positions (closed vs. open). The target registration error was computed in all 278 landmarks spread over the entire skull and mandible in 10 repeated measurements using the VectorVision^2 (BrainLAB Inc., Feldkirchen, Germany) navigation system.

Results

If registered in the closed position an average precision of 2.07mm with a standard deviation (SD) of 0.78mm was computed for all landmarks distributed over the whole skull. Registration in the open position resulted in an average precision of 1.53mm (SD=0.55mm). For single landmarks the precision decreases linearly with distance from the reference markers. The longer the three-dimensional distance between the registration points, the more precise the computer-navigation is, mainly in the most posterior area of the cranium.

Conclusion

Our findings in the cranium are comparable with those of other studies. Artificial fixation of the lower jaw via splint seems to introduce no additional error. The registration points should be as far apart from each other as possible during navigation with the splint.

INTRODUCTION

Computer navigation plays an increasingly important role in craniomaxillofacial surgery (Kawachi et al., 2010). The complex three-dimensional structure of the skull, and the necessary highly symmetric precision, is a huge challenge (Hassfeld and Muhling, 2001). Stereolithography models based on CT datasets are expensive and difficult to use (Hassfeld and Muhling, 1998). Planning based on these models is not transferable to the operating room in practice. Current computer-based three-dimensional CT datasets have opened the door to surgical navigation (Hassfeld and Muhling, 2000; Yeshwant et al., 2005a; Yeshwant et al., 2005b; Ritter et al., 2006; Luebbers et al., 2008), which does make planning transferrable to the operating room (Marmulla and Niederdellmann, 1998; Marmulla, 1999). This method is already widely used in craniomaxillofacial surgery (Hassfeld and Muhling, 2000; Gellrich et al., 2002; Schmelzeisen et al., 2002; Marmulla et al., 2004c; Schmelzeisen et al., 2004; Hohlweg-Majert et al., 2005).

The difficulty with this technique lies in the accurate transmission of the CTs to the operating room. Precise registration is crucial, as it has direct repercussions for the precision of all subsequent navigation tasks (Eggers et al., 2006; Luebbers et al., 2008). Several methods have been used to solve the registration problem. They can be split into two groups: marker-based registration (Altobelli et al., 1993; Hassfeld et al., 1995; Howard et al., 1995; Schramm et al., 1999; Luebbers et al., 2008) and marker-free registration (Troitzsch et al., 2003; Marmulla et al., 2004a; Hoffmann et al., 2005b; Marmulla et al., 2005; Luebbers et al., 2008). In marker-based registration, markers are applied during the CT procedure. These markers can easily be reproduced and stay where they are during the operation. They include (a) percutaneously inserted bone-implanted screws (Sinikovic et al., 2007), for example, on the orbital rim, (b) a referencing dental splint fitted to the maxillary teeth (Schramm et al., 2001), or (c) self-adhesive reference markers glued to the skin (Alp et al., 1998; Hardy et al., 2006). In contrast to these marker-based methods, marker-free registration relies on the patient's craniofacial anatomy itself. One approach is to register defined bone protuberances, for example, the anterior nasal spine (Swennen et al., 2006), to the corresponding structures apparent in CT bone scans (Grevers et al., 2002; Marmulla et al., 2004b; Hoffmann et al., 2005b). Another marker-free registration technique is laser surface scanning. This method matches random points on the facial skin surface to the soft tissues in the CT scan. Each one of these registration methods has disadvantages.

Particularly with the mandible, these errors can become large, as it has no bony structure connecting it to the viscerocranium. Unlike the rest of the craniomaxillofacial skeleton, which acts as one solid structure, the mandible is an independently moving body, and therefore, its synchronization with the CT scan is more difficult (Casap et al., 2008). For navigation of the mandible, the published data have described three techniques as feasible: (a) maxillomandibular fixation, which immobilizes the mandible (Lubbers et al., 2010), (b) positioning the mandible in another defined position against the maxilla using the occlusion or special templates (Watzinger et al., 1999; Schultes et al., 2003; Heiland et al., 2004; Casap et al., 2005; Hoffmann et al., 2005a; Casap et al., 2008), and (c) mounting a dynamic reference frame (DRF) to the mandible (Watzinger et al., 1999; Casap et al., 2004; Casap et al., 2008).

Our aim in this in vitro study was to determine the accuracy of the splint-based registration method, particularly looking at the mandible. Previous studies have evaluated general precision (Schlaier et al., 2002; Hoffmann et al., 2005b; Metzger et al., 2007) and concentrated on navigation precision in the maxillary and periorbital region (Marmulla et al., 2004b; Marmulla et al., 2004a; Hardy et al., 2006) or precision in the cranium (Luebbers et al., 2008). In contrast, this study examines precision beyond the cranium and the mandible and analyses the target registration error using two different dental splints. Cone beam computer tomography (CBCT) was used instead of conventional CT (Eggers et al., 2009), and for the registration points cheap titanium screws were used instead of special markers.

MATERIALS AND METHODS

Ten in vitro registrations were performed on a synthetic human skull model (A20, 3B Scientific, Hamburg, Germany) and navigated using the VectorVision^2 optical navigation system (BrainLAB Inc., Feldkirchen, Germany).

Skull preparation

The skull model was prepared with landmarks. The landmarks were created by drilling 1.2mm holes on the model. The landmarks were evenly spaced, with a special focus on clinically relevant, anatomically complex structures. A drilling diameter of 1.2mm was selected in order for the holes to be clearly visible during CBCT. One hundred and seventy landmarks were evenly spread over the viscerocranium and neurocranium, and 108 landmarks were evenly spread over the mandible.

Splint production

Two different splints were produced in order to fix the mandible against the viscerocranium. One splint fixed the mandible in an open position (Figure 1) and the other in a closed position (Figure 2).

Plaster models of the teeth were used to produce a vacuum-formed template. The template comprises five radio opaque markers (Titanium bone screw, Modus 1.5x6mm, Medartis, Basel, Switzerland), as reference points. This reference marker were fixed with PMMA (Paladur, Heraeus, Hanau, Germany) and positioned in different X, Y and Z directions. The aim was to get as big a polygon as possible. The two templates of the open splint were fixed against each other with PMMA. The closed splint was made with impressions from the upper teeth.

Cone Beam Computer Tomography (CBCT)

The skull model was scanned using high-definition CBCT (KaVo 3D eXam, KaVo Dental GmbH, Biberach/Riß, Germany). The 16cm Ø x 13cm dataset was acquired at a voxel size of 0.4mm. Because of the limited field of view of the CBCT scanner, the whole skull was not covered in one scan. Therefore, two scans of each skull had to be done. After importing the dataset into the BrainLAB iPlan CMF 2.5 software, the two scans were matched (Figure 3).

All landmarks, namely the screw heads and the drillings, were manually identified on the coronary, sagittal, and axial slices as well as on the three-dimensional surface (Figure 4). The three-dimensional dataset, along with the identified reference points, was transferred to the navigation system by ZIP-Disk.

Referencing and navigation

The BrainLAB navigation system (VectorVision^2) was set up in a partially obscured room. The skull was prepared with a reference star. This reference star is routinely deployed during clinical navigation. It is screwed securely into the calvarium. The skull was then registered with the aid of the registration splints. For each registration splint, all 278 drilled landmarks in the viscerocranium and mandible were targeted with a tracked pointer. Although the pointer was placed exactly on the landmarks, the navigation system recorded a fixed deviation, thus depicting the pointer head next to the landmark. The navigation software computes the target registration error (Fitzpatrick and West, 2001; Marmulla et al., 2004a) as the square root of the sum of squared deviation in all three spatial directions is $\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$. This deviation was recorded for each landmark and registration method. The complete experiment was repeated 10 times with each of the two registration splints (Luebbers et al., 2008).

Data evaluation

For each of the 278 landmarks, the referencing error was averaged over the 10 measuring channels. The examined landmarks were categorized into 16 anatomical regions. Each of these anatomical regions contained approximately 20 landmarks on the left and right side of the skull.

Graphical post-processing was performed in Matlab (Version 7.1/R14, TheMathworks Inc., Natick, USA). The distance between each landmark and the centre of gravity (COG) of the reference markers employed for referencing was calculated. The referencing error of each landmark as a function of the COG was demonstrated in a boxplot graph. To visualize the results better, a colorised map was wrapped around the virtual skull.

RESULTS

The target drillings could all be clearly identified on the reconstructed three-dimensional skull model in the iPlan (R) software. While repeating the measurements, no difficulties occurred. For each anatomical region, the average error was taken. Table 1 presents the results for all regions and the two splints. In both splints, the farther the landmark is away from the COG, the greater the error. This finding is shown in Figures 5a and 5b. The best precision was obtained in the maxillary region, where the average error ranged from 1.18mm (open splint) to 1.25mm (closed splint), depending on the employed registration technique. In the mandible, the best precision depended on the splint, between the mandibular body and muscular process.

The precision of the open splint in the most posterior skull area is significantly better than that for the closed splint. Concerning the leading skull area, the results are comparable. The regional precision after splint registration is best demonstrated by mapping the target errors onto a virtual three-dimensional model of the skull (Figures 6 and 7).

DISCUSSION

The results are comparable with those of other studies exploring the accuracy of computer navigation with a splint (Metzger et al., 2007; Luebbers et al., 2008). Our results are also comparable with those for other registration methods such as laser surface scanning, bone-implanted fiduciary markers, and anatomical structures (Schlaier et al., 2002; Marmulla et al., 2004a; Hoffmann et al., 2005b; Hardy et al., 2006; Pham et al., 2007). The use of a CBCT dataset seems to lead to the same results as those obtained with a CT dataset (Eggers et al., 2009).

The reason the open splint achieved better results is that the polygon of the registration points was bigger. Therefore, the distance between the registration points during computer navigation with the splint should be as large as possible.

An even higher precision in the maxillary area can be obtained by combining splint and bone anchored fiduciary markers, as Lübbers et al. demonstrated (Luebbers et al., 2008). In the most posterior skull area, the fiduciary markers provide no benefit as compared to the open splint, thus the assumed instability of the splint is not the reason for the inaccuracy in the posterior skull area. With larger distances between the registration points, the accuracy in the posterior region improves, as we showed with the closed splint, for which the distance is shorter. Further investigation should be done with larger distances between the registration points to improve the precision in the posterior skull area.

In conclusion, the accuracy of image-guided surgery depends on the geometry of the configuration of the registration points and its relation to the surgical target (Zhang et al., 2010).

To our knowledge, no comparable studies have investigated precision in the mandible. But our results with the open splint are comparable to those obtained in the upper jaw. The worst accuracy with the closed splint is obtained in the posterior ascending ramus. The reason for this finding is the mobile connection with the cranium. The splint is constructed with impressions for the upper jaw teeth and a vacuum-formed template for the lower teeth to simplify handling during the operation. The open splint consists of two vacuum-formed templates for the upper and lower teeth, which encase the teeth. This is not possible for practical reasons in the closed splint, as the mouth cannot be closed for an entire operation in most situations. Some of the inaccuracy in the mandible with the closed splint could be explained by the smaller registration point polygon, as with the findings in the cranium.

Solid artificial fixation of the lower jaw with templates encasing the teeth seems to introduce no additional error.

The skull used is an accurate reproduction of a human skull. The splints were produced as if they were used for normal patients and were worn in the CBCT. The splints were removed and remounted before each repeated measurement. Therefore the virtual results can be compared to those obtained during an actual operation.

The splint method brings great benefit: It is non-invasive and easy to do (Schramm et al., 2001) (Gellrich et al., 2002). However, some sources of error have to be considered using the splint method: First, the splint has to be worn during the primary image acquisition. Otherwise, a second image set has to be acquired prior to the operation (Widmann et al., 2009). Second, the construction of the open splint demands special skills. Instead of the technique described by Hoffmann et al. (Hoffmann et al., 2004), chairside fixation significantly reduces the laboratory work necessary and can provide a more optimal position of the lower jaw for both the patient's and surgeon's needs. Immobilisation of the mandible reduces soft tissue changes, especially in the region close to the mandible, its ascending ramus, and the masticatory muscles. This allows navigation not only of the bony structures but also in the soft tissues close to the bone (Lubbers et al., 2010). Third, the splint should be consistently relocatable during CBCT and surgery or great inaccuracy can result (Marmulla et al., 2003). Above all, in the mandible this problem is exacerbated because while pivoting, the splint has to stay in place. This can lead to problems with space in the operating room. “Any problems with the surgical view or instrument access can be immediately resolved by removing the splint. Additional navigation is possible immediately after repositioning the splint” (Lubbers et al., 2010). Fourth, one must consider potentially bad seating of the patients' teeth, which can also decrease the accuracy. With edentulous patients, this method is therefore inappropriate

(Schramm et al., 2001). Attempts with fiduciary markers mounted on a prosthesis or a registration splint placed on a prosthesis have been successful. However, a systematic evaluation of the accuracy achieved for this special situation has not been performed yet, and therefore, we cannot recommend routine use.

CONCLUSION

The accuracy of image-guided surgery depends on the geometry of the registration point configuration and its relation to the surgical target. This splint technique is mainly useful for navigation of the midface and mandible but yields poorer precision beyond that. Further studies have to be done to improve the accuracy mainly in the posterior areas of the cranium with greater polygons. Solid artificial fixation of the lower jaw seems to introduce no additional error. The use of a CBCT dataset seems to lead to the same results as those achieved with a CT dataset.

CONFLICT OF INTEREST STATEMENT

All authors declare that they have no financial and personal relationships with other people or organisations that could inappropriately influence (bias) this work. The work was not funded from any party.

CAPTIONS

Table 1: Target registration error in different regions for the closed and open splint

Figure 1: Skull model with mounted open splint.

Figure 2: Skull model with mounted closed splint.

Figure 3: Matching the two CBCT scans in the BrainLAB iPlan ENT 2.6 software.

Figure 4: Three-dimensional view of the skull model using the pre-operative planning software (iPlan, BrainLAB) with the identified landmarks.

Figure 5a: Correlation between target registration error and distance from center of gravity of the fiduciary markers for closed splint technique.

Figure 5b: Correlation between target registration error and distance from center of gravity of the fiduciary markers for open splint technique.

Figure 6: Target registration error mapped onto the 3D surface model for the closed splint. Color coding: Green <1.5mm, yellow 1.5-2.5mm, red >2.5mm target registration error.

Figure 7: Target registration error mapped onto the 3D surface model for the open splint. Color coding: Green <1.5mm, yellow 1.5-2.5mm, red >2.5mm target registration error.

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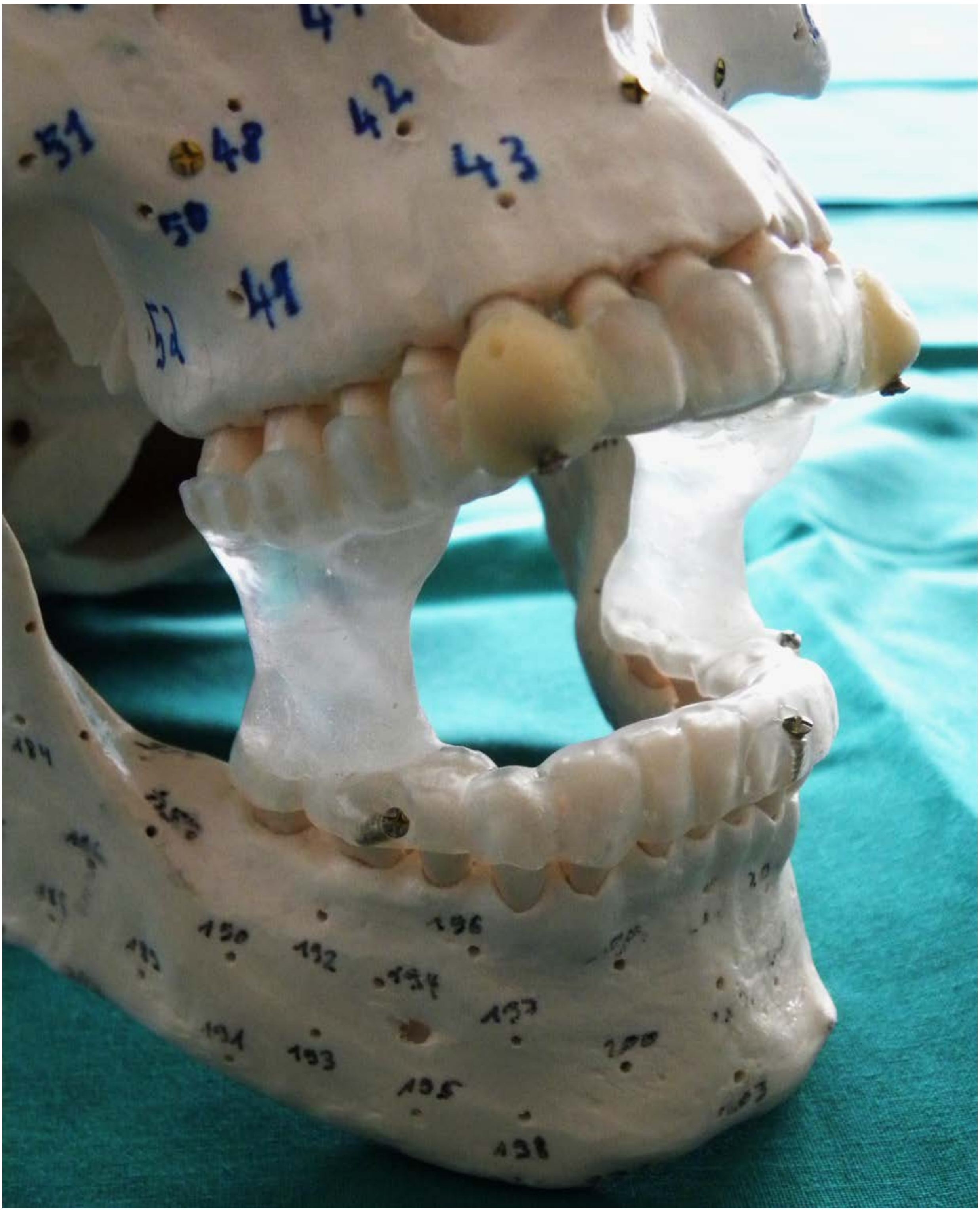
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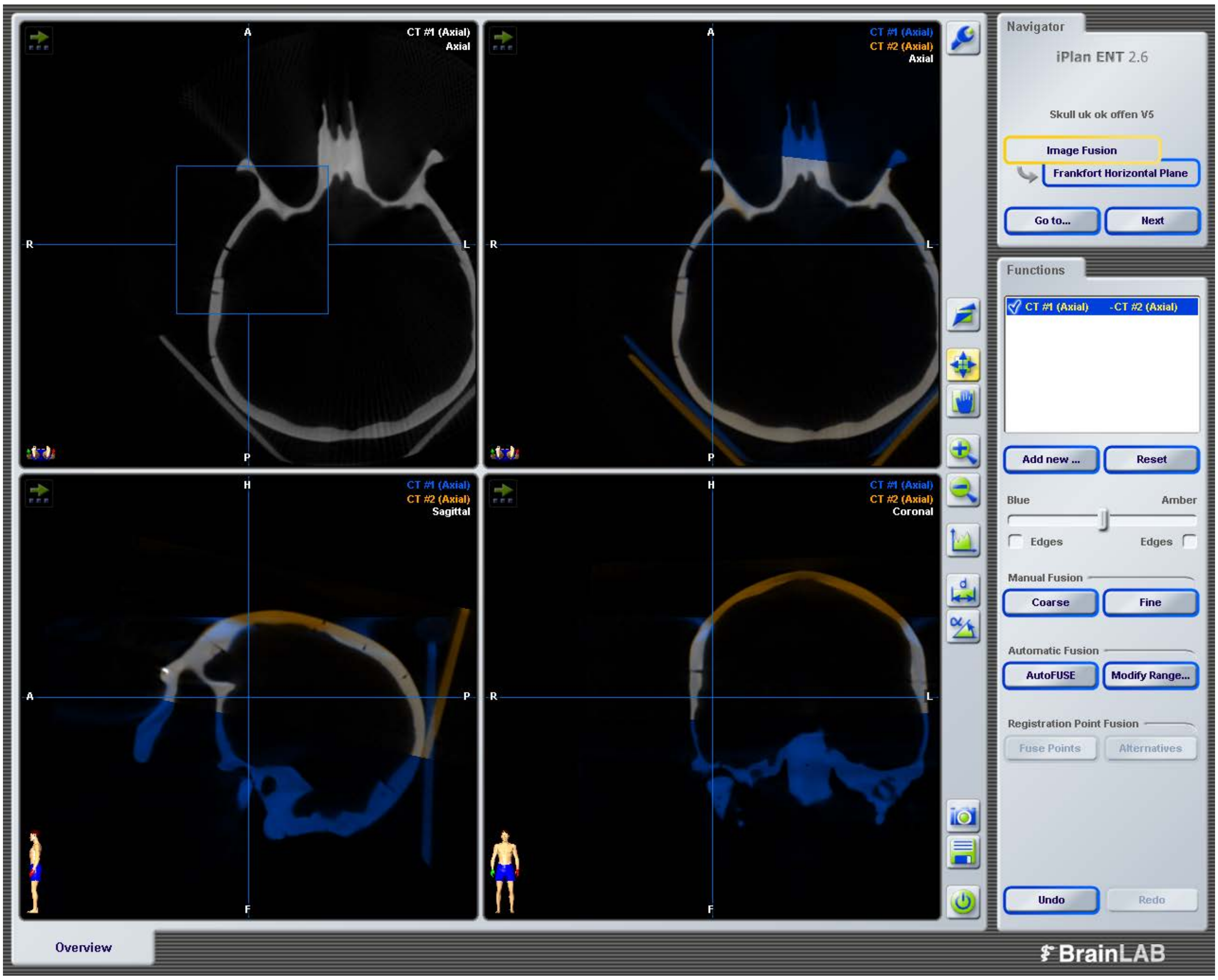

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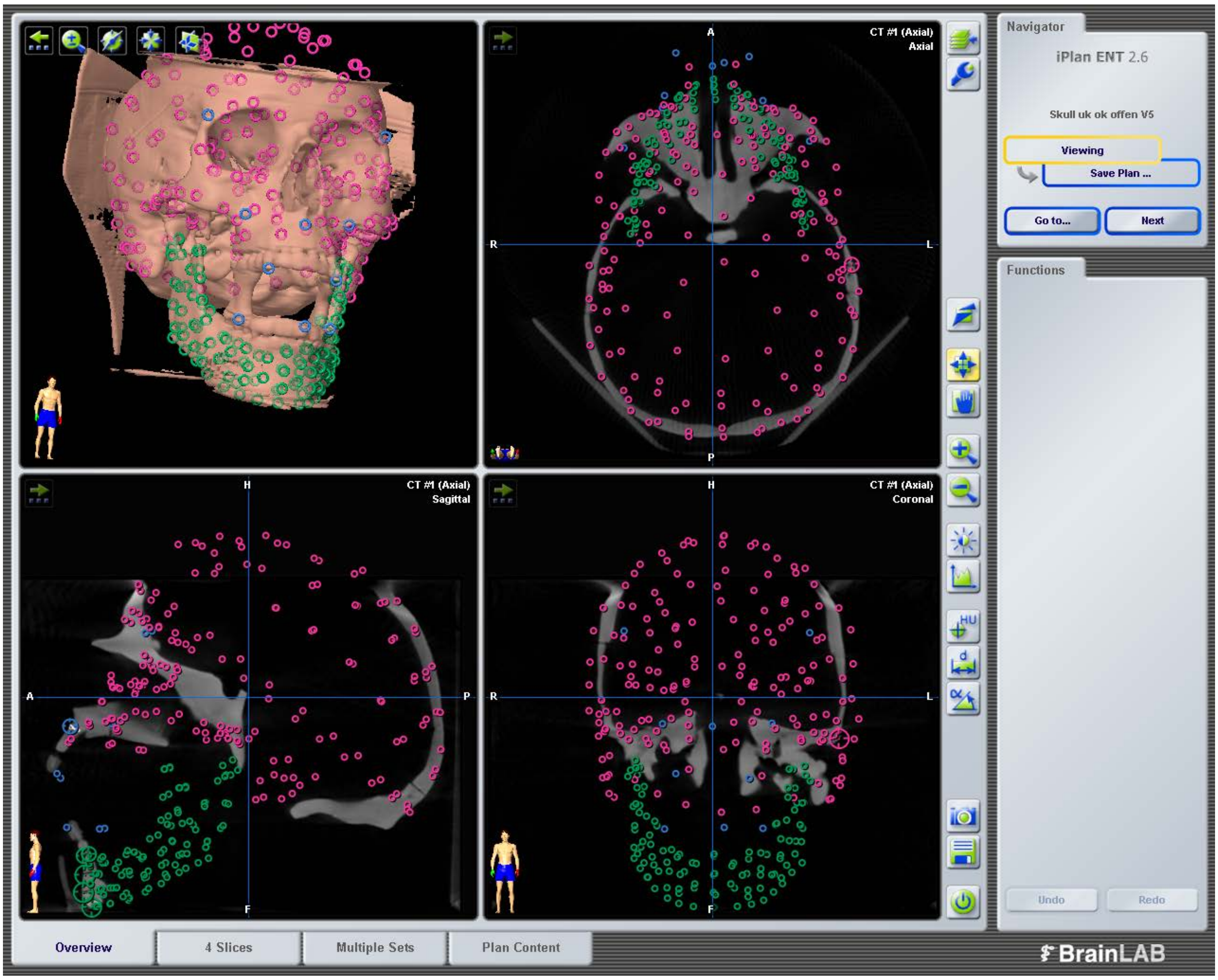
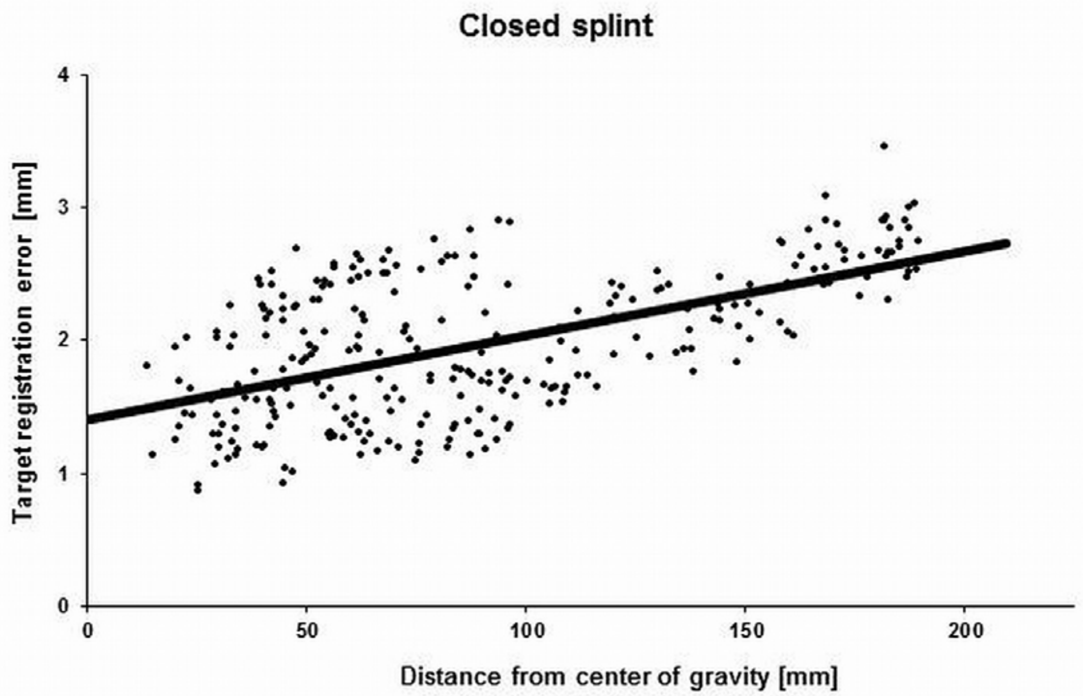
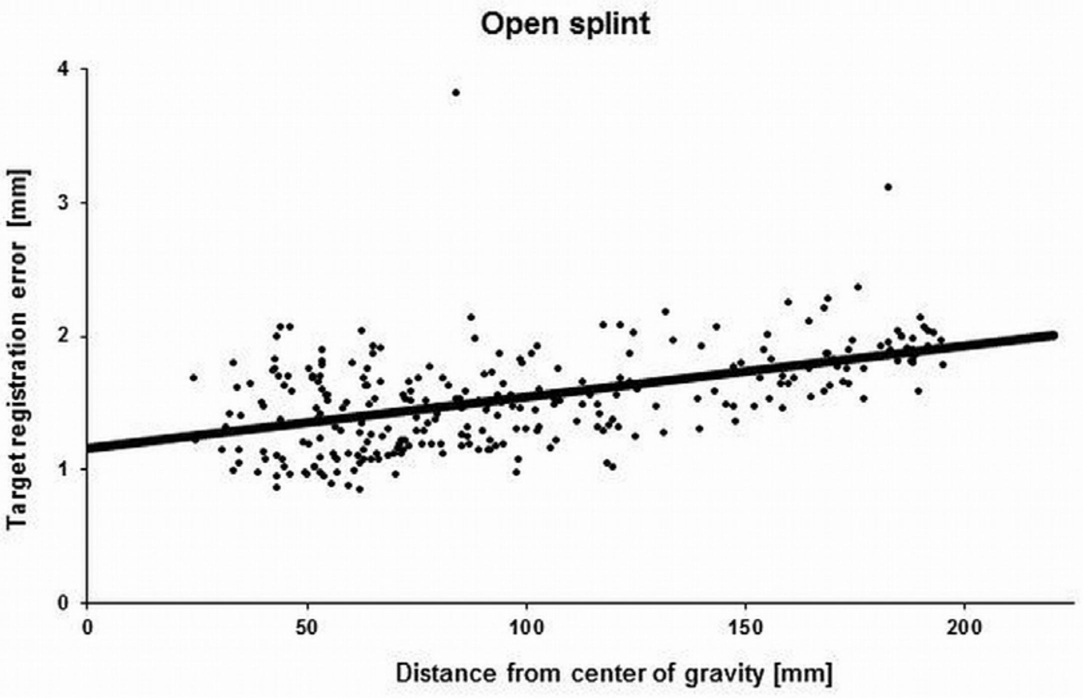
Overview
BrainLAB


Navigator
iPlan ENT 2.6
Skull uk ok offen V5
Viewing
Save Plan ...
Go to...
Next
Functions
Undo
Redo
CT #1 (Axial)
Axial
CT #1 (Axial)
Sagittal
CT #1 (Axial)
Coronal
A
P
R
L
H
F
HU
Overview
4 Slices
Multiple Sets
Plan Content
BrainLAB



Closed splint
Target registration error [mm]
Distance from center of gravity [mm]
0
1
2
3
4
0
50
100
150
200



Open splint
Target registration error [mm]
Distance from center of gravity [mm]
0
1
2
3
4
0
50
100
150
200